Limits to Arbitrage in Markets with Stochastic Settlement Latency

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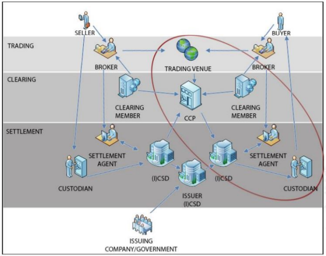
What makes a blockchain market different from a "traditional" market?



- No intermediaries (e.g., for clearing)
- Settlement much faster
- Trust through proof of work
- Security through complexity of verification
- On a public blockchain, transactions are (semi-)transparent
- ...

Blockchain technology and stochastic latency

In "classical" markets, process of trading and process of ownership transfer are disconnected.

- Both transacting parties face counterparty risks during settlement period (1-2 trading days).
- (Third-party) central clearing allows for continuous (high-frequency) trading on <u>non-settled</u> positions.

In (pure) distributed ledger systems, transfer of ownership is connected to trading.

- Funds can<u>not</u> be further transfered before transaction is validated.
- Process of validation takes time ($>$30min): Consensus algorithms introduce *stochastic latency*

What are the implications of stochastic latency for arbitrage?

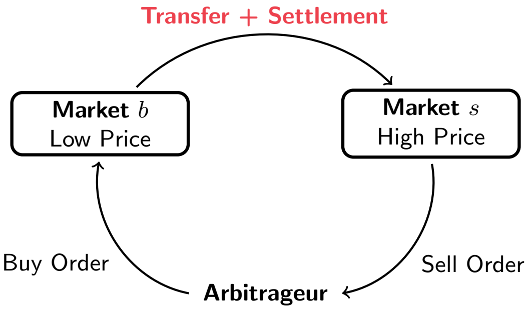
Stochastic latency through the blockchain

Market b
Low Price

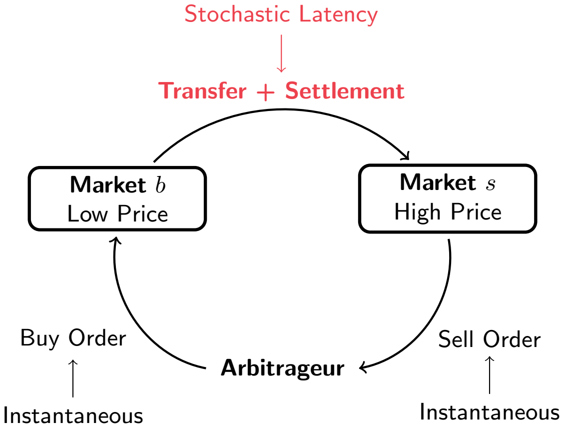
Market s
High Price

Arbitrageur

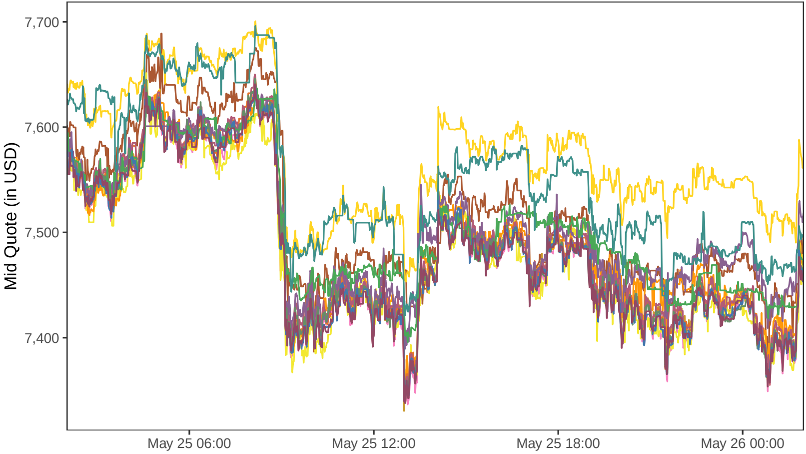
Stochastic latency through the blockchain



Stochastic latency through the blockchain



Arbitrage possibilities in BTC-USD trading on May 25, 2018?



This paper

Research question:

- How much of observed cross-market price differences are explained by limits to arbitrage due to (stochastic) latency?

This paper:

- Derivation of arbitrage bounds for markets with stochastic latency
- In-depth analysis of Bitcoin network based on limit order book data of 16 exchanges
- Estimation of arbitrage bounds and analysis of arbitrage opportunities in the BTC vs. USD market

2. Stochastic Latency and Limits to Arbitrage

Market $i \in \{1, ..., N\}$ continuously provides buy quotes (ask) A_t^i and sell quotes (bid) B_t^i for one unit of the asset where $B_t^i \leq A_t^i$ at time t.

No short selling, margin trading or derivatives

Arbitrageur continuously monitors the quotes on markets b and s.

Instantaneous trading: Arbitrageur exploits price differences if

$$B_t^s - A_t^b > 0$$

Stochastic latency τ is the random waiting time until a transfer of the asset between markets is settled.

Profit of arbitrageur's trading decision if

$$\mathbb{P}\left(B_{t+\tau}^s \leq A_t^b | \mathcal{I}_t\right) > 0.$$

Log return of arbitrageur's strategy

$$r^{b,s}_{(t:t+\tau)} = b^s_{t+\tau} - a^b_t = \underbrace{\delta^{b,s}_t}_{\text{instantaneous return}} + \underbrace{b^s_{t+\tau} - b^s_t}_{\text{exposure to price risk}},$$

where $\delta^{b,s}_t = b^s_t - a^b_t$

Assumption 1. For given latency τ, we model the log price changes on the sell-side $b^s_{t+\tau} - b^s_t$ as a Brownian motion with drift μ^s_t such that

$$r^{b,s}_{(t:t+\tau)} = \delta^{b,s}_t + \tau\mu^s_t + \int_t^{t+\tau} \sigma^s_t dW^s_k,$$

We assume that μ^s_t and σ^s_t are locally constant over the interval $[t, t+\tau]$.

Assumption 2. Stochastic latency $\tau \in \mathbb{R}_+$ is a random variable equipped with a (conditional) probability distribution $\pi_t(\tau) := \pi\left(\tau|\mathcal{I}_t\right)$. We assume that all moments of τ are finite.

Lemma. Under Assumptions 1 and 2, the arbitrage returns follow a normal mean-variance mixture with probability distribution

$$\pi_t\left(r^{b,s}_{(t:t+\tau)}\right) = \int_{\mathbb{R}_+} \pi_t\left(r^{b,s}_{(t:t+\tau)}|\tau\right)\pi_t\left(\tau\right)d\tau$$

and characteristic function $\varphi_x(t) = \mathbb{E}[e^{it}x]$,

$$\varphi_{r^{b,s}_{t:t+\tau}}(u) = e^{iu\delta^{b,s}_t} m_\tau\left(iu\mu^s_t - \frac{1}{2}u^2(\sigma^s_t)^2\right),$$

where $m_\tau\left(u\right) := \mathbb{E}_t\left(e^{u\tau}\right)$ is the moment-generating function of $\pi_t(\tau)$.

Example: Exponential distribution

- P.d.f. of stochastic latency: $\pi_t(\tau) = \lambda_t e^{-\lambda_t \tau}$, with moment generating function $m_\tau(u) = \left(1 - \lambda_t^{-1} u\right)^{-1}$.
- The characteristic function of the mixture is

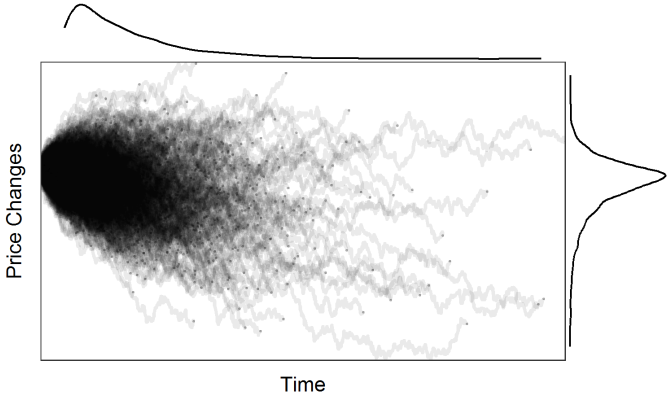
$$\varphi_{r^{b,s}_{t:t+\tau}}(u) = \frac{e^{iu\delta_t^{b,s}}}{1 - i\frac{\mu_t^s}{\lambda_t}u + \frac{\left(\sigma_t^s\right)^2}{2\lambda_t}u^2},$$

corresponding to the characteristic function of an asymmetric Laplace distribution (Kotz, Kozubowski, Podgorski, 2001) with

$$\mathbb{E}_t\left(r^{b,s}_{t:t+\tau}\right) = \delta_t^{b,s} + \frac{\mu_t^s}{\lambda_t}$$

$$\mathbb{V}_t\left(r^{b,s}_{t:t+\tau}\right) = \frac{1}{\lambda_t}\left(\left(\mu_t^s\right)^2 + \left(\sigma_t^s\right)^2\right).$$

Distribution of returns under exponential latency and negative drift
⇒ Asymmetric Laplace



Example: Inverse gamma distribution

- P.d.f. of inverse Gamma latency:

$$\pi_t(\tau) = \frac{\beta_t^{\alpha}}{\Gamma(\alpha)} \tau^{-(\alpha+1)} \exp\left(-\frac{\beta_t}{\tau}\right),$$

with $\mathbb{E}_t(\tau) = \frac{\beta_t}{\alpha-1}$ and $\mathbb{V}_t(\tau) = \frac{\beta_t^2}{(\alpha-1)^2(\alpha-2)}$, where $\Gamma(\alpha)$ denotes the Gamma function.

- Then, the conditional distribution of the returns of the arbitrageur's future returns $r_{(t:t+\tau)}^{b,s}$ corresponds to a non-standard Student's t distribution with p.d.f. given by

$$\pi_t\left(r_{(t:t+\tau)}^{b,s}\right) = \frac{\Gamma\left(\frac{2\alpha+1}{2}\right)}{\Gamma(\alpha)\sqrt{2\pi(\sigma_t^s)^2\beta_t}} \left(1 + \frac{(r_{(t:t+\tilde{\tau})}^{b,s} - \delta_t^{b,s})^2}{\alpha(\sigma_t^s)^2\beta_t}\right)^{-\frac{2\alpha+1}{2}},$$

with $\mathbb{E}_t\left(r_{(t:t+\tau)}^{b,s}\right) = \delta_t^{b,s}$ and $\mathbb{V}_t\left(r_{(t:t+\tau)}^{b,s}\right) = \frac{(\sigma^s)^2\beta_t}{\alpha-1}$.

Risk Aversion ...

Assumption 3. The arbitrageur has an utility function $U_\gamma(r)$ with risk aversion parameter $\gamma > 1$, and $U'_\gamma(r) > 0$ and $U''_\gamma(r) < 0$.

Arbitrageur exploits price differences if and only if the **certainty equivalent** of trading,

$$\mathbb{E}\left(U_\gamma\left(r^{b,s}_{(t:t+\tau)}\right)\right) = U_\gamma\left(CE\right),$$

is **positive**.

Theorem. Under Assumptions 1-3, the certainty equivalent (CE) is given by

$$\begin{aligned} CE = {} & \delta^{b,s}_t + \mathbb{E}_t(\tau)\mu^s_t \\ & + \sum_{k=2}^{\infty}\left(\frac{U^{(k)}_\gamma\left(\delta^{b,s}_t + \mathbb{E}_t(\tau)\mu^s_t\right)}{k!U'_\gamma\left(\delta^{b,s}_t + \mathbb{E}_t(\tau)\mu^s_t\right)}\mathbb{E}\left(\left(r^{b,s}_{(t:t+\tau)} - \delta^{b,s}_t - \mathbb{E}_t(\tau)\mu^s_t\right)^k\right)\right), \end{aligned}$$

where $U^{(k)}_\gamma\left(\mu_r\right) := \frac{\partial^k}{\partial \mu_r^k}U_\gamma\left(\mu_r\right)$

Arbitrage bound

The arbitrage boundary d_t^s is defined as the minimum price difference necessary such that the arbitrageur prefers to trade if $\delta_t^{b,s} > d_t^s$.

Definition. d_t^s is the maximum of zero and the (unique) root of

$$F(d) = d + \mathbb{E}_t(\tau)\mu_t^s + \sum_{k=2}^{\infty} \frac{U_\gamma^{(k)}\left(d + \mathbb{E}_t(\tau)\mu_t^s\right)}{k! U_\gamma'\left(d + \mathbb{E}_t(\tau)\mu_t^s\right)} \mathbb{E}_t\left(\left(r_{(t:t+\tau)}^{b,s} - d - \mathbb{E}_t(\tau)\mu_t^s\right)^k\right)$$

Price differences below the arbitrage boundary might persist as the arbitrageur prefers not to trade in such a scenario.

Constant absolute risk aversion (CARA)

Assumption. The arbitrageur is equipped with constant absolute risk aversion and exponential utility function $U_\gamma(r) := \frac{1-e^{-\gamma r}}{\gamma}$ with risk aversion parameter $\gamma > 1$.

Lemma. In case of an exponential utility function and the assumptions above, price differences are exploited if

$$CE > 0 \;\Leftrightarrow \delta_t^{b,s} > d_t^s,$$

with

$$\begin{aligned}
d_t^s := & -\mathbb{E}_t\left(\tau\right)\mu_t^s + \frac{\gamma}{2}\left(\mathbb{V}_t\left(\tau\right)\left(\mu_t^s\right)^2 + \left(\sigma_t^s\right)^2\mathbb{E}_t\left(\tau\right)\right) \\
& - \frac{\gamma^2}{6}\left(3\mu_t^s\left(\sigma_t^s\right)^2\mathbb{V}_t\left(\tau\right) + \left(\mu_t^s\right)^3\mathbb{E}_t\left(\left(\tau - \mathbb{E}_t\left(\tau\right)\right)^3\right)\right) \\
& + \frac{\gamma^3}{24}\left(\left(\mu_t^s\right)^4\mathbb{E}_t\left(\left(\tau - \mathbb{E}_t\left(\tau\right)\right)^4\right) + 6\left(\sigma_t^s\right)^2\left(\mu_t^s\right)^2\left(\mathbb{E}\left(\tau\right)^3 + \mathbb{E}_t\left(\tau^3\right) - 2\mathbb{E}_t\left(\tau\right)\mathbb{E}_t\left(\tau\right)\right)\right) \\
& + \frac{\gamma^3}{24}\left(3\mathbb{E}_t\left(\tau^2\right)\left(\sigma_t^s\right)^4\right)
\end{aligned}$$

Lemma. Under the above assumptions with $\mu_t^s = 0$, exponential utility and any well defined latency distribution, the arbitrage bound is given by

$$d_t^s = \frac{1}{2}\gamma(\sigma_t^s)^2\mathbb{E}_t(\tau) + \frac{1}{8}\gamma^3(\sigma_t^s)^4\mathbb{E}_t(\tau^2).$$

Stochastic latency implies limits to arbitrage, which increase if

- spot volatility is high
- expected latency is large
- latency uncertainty is high
- risk aversion is high

Constant relative risk aversion (CRRA)

- Arbitrageur has power utility function

$$U_\gamma(r) := \frac{r^{1-\gamma} - 1}{1-\gamma},$$

with relative risk aversion parameter $\gamma > 1$.

- Then, the arbitrage bound for $\mu_t^s = 0$ is given by

$$d_t^s = \frac{1}{2}\sigma_t^s \sqrt{\gamma \mathbb{E}_t\left(\tau\right) + \sqrt{\gamma^2 \mathbb{E}_t\left(\tau\right)^2 + 2\gamma(\gamma+1)(\gamma+2)\mathbb{E}_t\left(\tau^2\right)}}.$$

3. Transaction Costs & Settlement Fees

Transaction costs

- Consider proportional transaction costs of the form

$$B_t^i(q) = B_t^i \left(1 - \rho^{i,B}(q)\right)$$
$$A_t^i(q) = A_t^i \left(1 + \rho^{i,A}(q)\right),$$

  with $\rho^{i,B}(q) > 0$ and $\rho^{i,A}(q) > 0$ denoting transaction cost functions in dependence of the trading volume $q > 0$.

- Log return of arbitrage strategy changes to

$$\tilde{r}_{(t:t+\tilde{\tau})}^{b,s} = r_{(t:t+\tilde{\tau})}^{b,s} - \ln\left(\frac{1+\rho^{b,A}(q)}{1-\rho^{s,B}(q)}\right).$$

- **Lemma.** Arbitrageur exploits price differences if

$$\delta_t^{b,s} - \ln\left(\frac{1+\rho^{b,A}(q)}{1-\rho^{s,B}(q)}\right) > d_t^s$$

  for given quantity $q > 0$.

Latency-reducing settlement fees

- **Assumption.** A settlement fee $f > 0$ implies a latency distribution $\pi_t(\tau|f)$ that can be ordered in the sense that for $\tilde{f} > f$, $\pi_t(\tau|f)$ first-order stochastically dominates $\pi_t\left(\tau|\tilde{f}\right)$, i.e., $\mathbb{P}\left(\tau \leq x|\tilde{f}\right) > \mathbb{P}(\tau \leq x|f)$ for all $x \in \mathbb{R}_+$.
- Denote by $d_t^s(f)$ the arbitrage boundary associated with the latency distribution $\pi_t(\tau|f)$. Then, $d_t^s(f) > d_t^s(\tilde{f})$.
- Arbitrageur's trading decision features trade-off between q and f with endogenous arbitrage boundaries.
- **Lemma.** Under the given assumptions the arbitrageur prefers to trade a quantity $q > 0$ and pay a settlement fee $f > 0$ over staying idle if

$$\delta_t^{b,s} - \ln\left(\frac{1+\rho^{b,A}(q+f)}{1-\rho^{s,B}(q)}\right) > d_t^s(f).$$

- Arbitrageur maximizes

$$\max_{\{q,f\}\in\mathbb{R}^2_+} B_t^s \left(1-\rho^{s,B}(q)\right) q - A_t^b(1+\rho^{b,A}(q+f))(q+f)$$

subject to

$$\delta_t^{b,s} - \ln\left(\frac{1+\rho^{b,A}(q+f)}{1-\rho^{s,B}(q)}\right) \geq d_t^s(f).$$

Lemma. A total return maximizing arbitrageur chooses trading quantities $q^* > 0$ and settlement fees $f^* \geq 0$ such that

$$\delta_t^{b,s} - \ln\left(\frac{1+\rho^{b,A}(q^*+f^*)}{1-\rho^{s,B}(q^*)}\right) = d_t^s(f^*).$$

He pays $f^* > 0$ to trade $q^* > 0$ if the following necessary conditions are met:

$$\frac{1-\rho^{s,B}(q^*)}{q^*} > \rho^{s,B'}(q^*)$$

$$-\frac{\partial}{\partial f} d_t^s(f^*) > \frac{\rho^{s,B'}(q^*)}{1+\rho^{s,B}(q^*)}.$$

Otherwise, the arbitrageur optimally sets $f^* = 0$.

4. Data

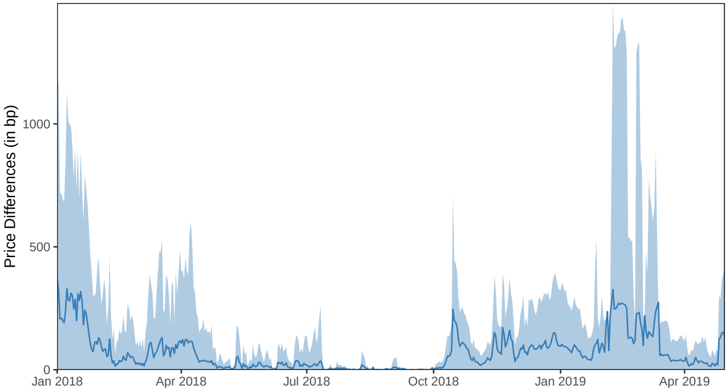
Bitcoin orderbook data

Minute-level Bitcoin/Dollar orderbooks from 16 large exchanges ($\approx 95\%$ of trading volume)

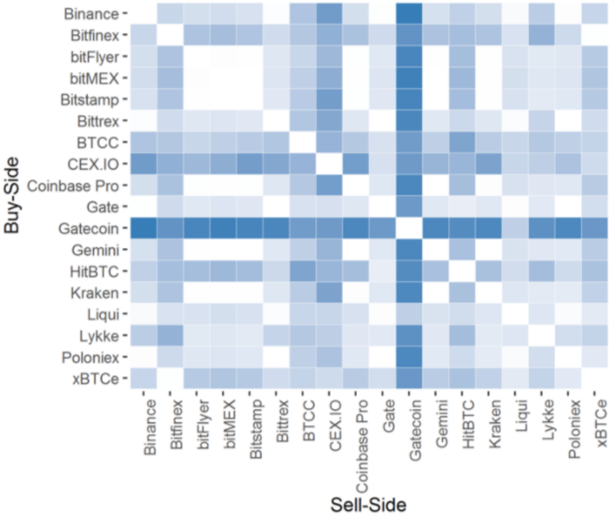
Buy and sell orders for the first 25 levels since April 2018.

	Orderbooks	Spread (USD)	Spread (bp)	Taker Fee	With. Fee	Conf.	Margin
Binance	677,930	2.88	3.77	0.10	0.10	2	TRUE
Bitfinex	676,019	0.52	0.68	0.20	0.08	3	TRUE
bitFlyer	656,244	12.80	19.95	0.15	0.08		TRUE
Bitstamp	675,256	4.53	6.09	0.25	0.00	3	FALSE
Bittrex	677,298	10.13	15.63	0.25	0.00	2	FALSE
CEX.IO	674,595	10.37	14.56	0.25	0.10	3	TRUE
Gate	644,379	108.80	122.00	0.20	0.20	2	FALSE
Coinbase Pro	678,216	0.14	0.24	0.30	0.00	3	TRUE
Gemini	651,425	2.00	3.08	1.00	0.20	3	FALSE
HitBTC	656,195	3.19	4.20	0.10	0.08	2	FALSE
Kraken	673,730	2.74	3.56	0.26	0.10	6	TRUE
Liqui	491,516	30.15	45.13	0.25			TRUE
Lykke	655,407	34.03	51.37	0.00	0.05	3	FALSE
Poloniex	654,104	5.46	8.25	0.20		1	TRUE
xBTCe	623,912	8.36	13.67	0.25	0.30	3	TRUE

Avg. price differences (after transaction costs)



Average cross-market price differences



Bitcoin blockchain mempool

- Data from `www.blockchain.com`
- All confirmed blocks from January 2018 until April 2019
- 92,626,780 transactions verified in 71,992 blocks
- For each transaction: unique ID, size, fee, latency

	Mean	SD	5 %	25 %	Median	75 %	95 %
Fee per Byte (Satoshi)	48.79	219.48	1.53	4.59	10.75	32.00	282.49
Fee per Transaction (USD)	2.09	29.13	0.02	0.07	0.18	0.62	10.84
Latency	38.71	335.02	0.73	3.55	8.75	20.10	92.42
Transaction Size	527.57	2274.81	192.00	225.00	247.00	372.00	963.00
Mempool Size	8437.26	14438.03	324.00	1336.00	3429.50	8064.50	39415.00
Block Validation Time	9.70	9.62	0.55	2.85	6.77	13.42	28.95

5. Quantifying Arbitrage Bounds

Limits to arbitrage for CRRA case are given by

$$\hat{d}_t^s = \frac{1}{2}\hat{\sigma}_t^s\sqrt{\gamma\hat{\mathbb{E}}_t(\tau) + \sqrt{\gamma^2\hat{\mathbb{E}}_t(\tau)^2 + 2\gamma(\gamma+1)(\gamma+2)\hat{\mathbb{E}}_t(\tau^2)}}.$$

Ingredients:

1. Spot volatility $(\hat{\sigma}_t^s)^2$
2. Estimates of $\mathbb{E}_t(\tau)$ and $\mathbb{E}_t(\tau)^2$.
3. Estimates of $\rho^{b,A}(q)$ and $\rho^{s,B}(q)$ for optimal q.

Estimating spot volatilities σ_t^s

- Current volatility affects price risk of arbitrageur

$$db_t^s = \sigma_t^s dW_t^s$$

- Nonparametric filtering of the realized spot volatility (Kristensen, 2010)
- For each market n and time t, we estimate $(\sigma_t^n)^2$ by

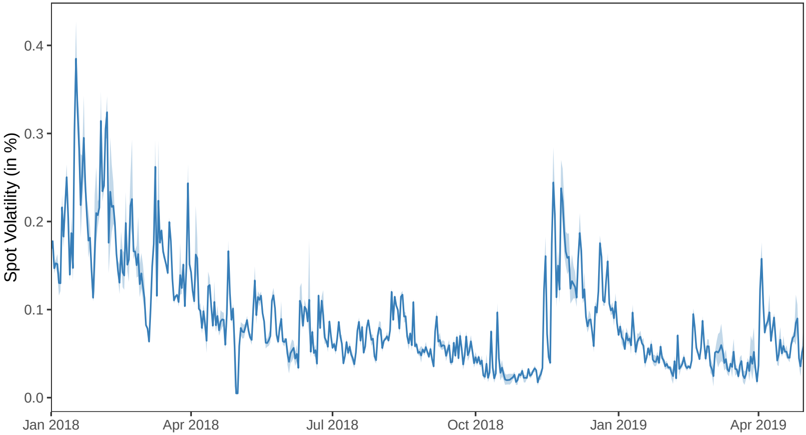
$$\widehat{(\sigma_t^n)}^2(h) = \sum_{s=1}^{t} K(s-t,h)\left(b_s^n - b_{s-1}^n\right)^2,$$

  where $K(s-t,h)$ denotes a one-sided Gaussian kernel smoother with bandwidth h.
- Bandwidth h chosen by minimizing the Integrated Squared Error (ISE)

$$\widehat{\mathsf{ISE}}_{T-1}(h) = \sum_{i=1}^{I}\left[\left(b_i^n - b_{i-1}^n\right)^2 - \widehat{(\sigma_i^n)}^2(h)\right]^2,$$

  where $i = 1, \ldots, I$ refers to the observations on day $T-1$ and $\widehat{(\sigma_t^n)}^2(h)$ is the spot volatility estimator based on bandwidth h.

Daily cross-exchange averages of spot volatilities



Parameterizing waiting times $\pi(\tau_t|\mathcal{I}_t)$

- Exponential model:

$$\pi_t(\tau_i) = \lambda_i \exp(-\lambda_i \tau_i),$$
$$\lambda_i = \exp(-x_i' \theta_t),$$

- Gamma model:

$$\pi_t(\tau_i) = \frac{\beta_i \alpha}{\Gamma(\alpha)} \tau^{\alpha-1} e^{-\beta_i \tau_i}$$
$$\beta_i = \exp(-x_i' \theta_t), \alpha > 0$$

- Covariates x_i: number of unconfirmed transactions in mempool; network fee per byte

Parameter estimates

	Exponential		Gamma	
	W/o Covariates	W/ Covariates	W/o Covariates	W/ Covariates
Intercept	3.02 [2.442 , 3.687]	1.13 [-0.043 , 2.549]	3.4 [2.514 , 4.379]	1.15 [-0.021 , 2.406]
α			0.7 [0.487 , 0.95]	0.72 [0.505 , 0.945]
Fee per Byte		-0.04 [-0.082 , -0.005]		-0.02 [-0.082 , -0.005]
Mempool Size		2.04 [0.221 , 3.528]		2.43 [0.535 , 4.099]
LR (Covariates)	93.61		84.33	
LR (Gamma vs. Exponential)	92.58			
MSPE (Out of Sample)	37.77	37.44	37.77	37.58
MSPE (In Sample)	35.82	35.22	35.82	35.29

- Higher fees reduce latency (Easley et al, 2019)
- Blockchain congestion increases latency

Estimation of arbitrage bounds

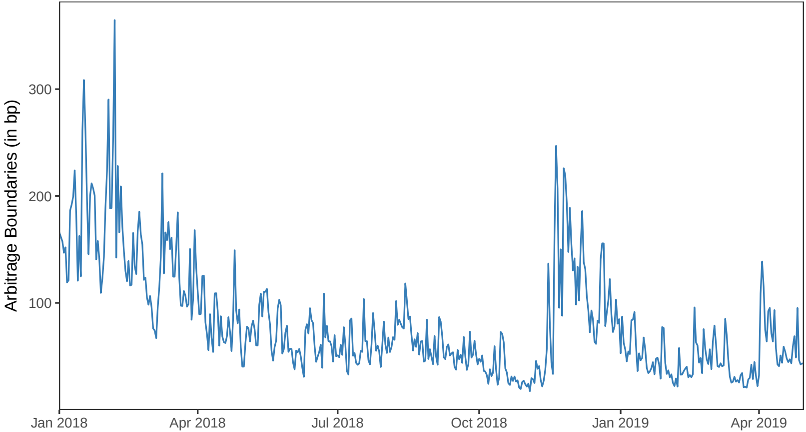
- Limits to arbitrage for CRRA case are given by

$$\hat{d}_t^s = \frac{1}{2}\hat{\sigma}_t^s \sqrt{\gamma c_1 + \sqrt{\gamma^2 c_1^2 + 2\gamma(\gamma+1)(\gamma+2)c_2}},$$
$$c_1 = \hat{\mathbb{E}}_t\left(\tau\right) + \hat{\mathbb{E}}\left(\tau_B\right) \cdot \left(B^s - 1\right)$$
$$c_2 = \hat{\mathbb{V}}_t\left(\tau\right) + \hat{\mathbb{V}}\left(\tau_B\right) \cdot \left(B^s - 1\right)^2 + \left(\hat{\mathbb{E}}\left(\tau_B\right) \cdot \left(B^s - 1\right) + \hat{\mathbb{E}}_t\left(\tau\right)\right)^2,$$

  where B^s refers to the number blocks that the sell-side exchange s requires to consider incoming transactions as valid.

- $\widehat{\mathbb{E}}_t\left(\tau_i\right)$ and $\widehat{\mathbb{V}}_t\left(\tau_i\right)$ computed based on (rolling window) day $T-1$ parameter estimates.

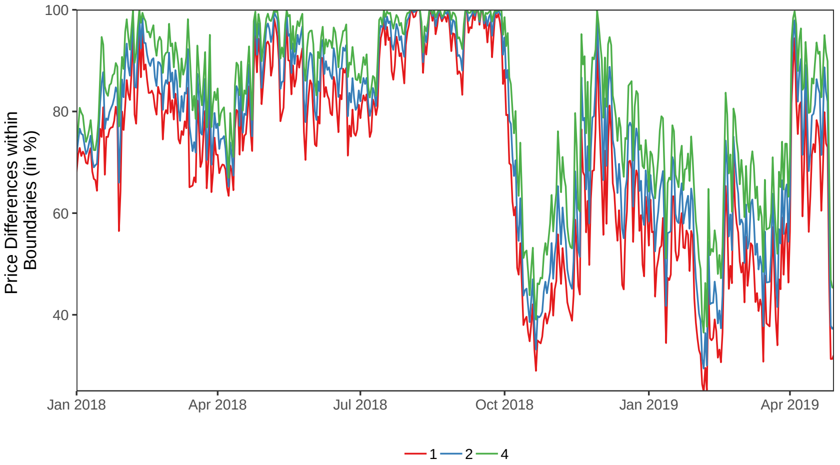
Estimated arbitrage bounds over time ($\gamma = 2$)



Estimated arbitrage bounds (in bps, $\gamma = 2$)

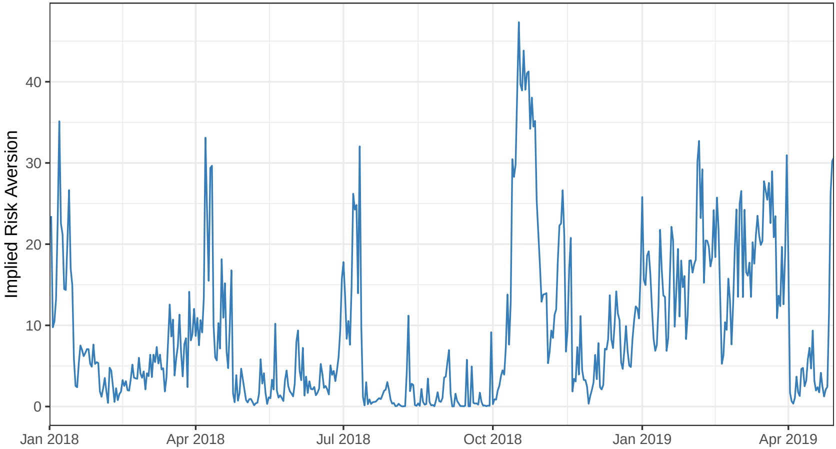
- Average boundary about 96bps
- Latency uncertainty accounts for 9% on average

	Mean	SD	5%	25%	Median	75%	95%	Uncertainty	Security
Binance	77.09	62.84	20.41	35.47	56.77	97.75	199.73	9.00	18.98
Bitfinex	84.01	69.10	15.38	35.37	62.42	113.17	222.94	8.46	31.49
bitFlyer	92.98	65.72	28.72	50.39	73.49	113.91	223.44	8.46	31.53
Bitstamp	91.55	69.67	24.35	44.05	69.46	118.17	230.76	8.56	31.14
Bittrex	98.30	63.45	28.79	54.26	83.23	124.56	219.35	8.57	20.11
CEX.IO	88.90	61.98	25.32	45.58	72.37	112.11	213.13	8.42	31.73
Gate	73.45	54.07	19.89	37.20	58.19	92.44	178.68	8.77	19.63
Gatecoin	185.74	211.13	2.70	44.90	112.77	253.63	606.39	9.14	50.98
Coinbase Pro	78.83	66.43	14.51	32.86	58.54	103.35	213.89	8.56	31.99
Gemini	80.81	66.12	17.48	35.99	60.55	103.73	216.48	8.57	31.68
HitBTC	66.70	56.45	15.39	30.05	49.73	83.98	175.08	8.84	19.69
Kraken	107.08	84.59	21.26	46.79	80.83	143.14	282.51	9.15	49.91
Liqui	81.99	48.51	22.02	47.69	73.41	105.93	170.37	8.27	33.40
Lykke	92.38	86.87	13.83	35.99	65.35	116.95	265.90	8.53	31.52
Poloniex	59.68	51.21	14.21	27.04	43.77	74.66	158.05	13.76	0.00
xBTCe	82.70	69.44	15.21	34.73	61.46	110.61	219.68	8.56	31.46



Price Differences within Boundaries (in %)
100
80
60
40
Jan 2018
Apr 2018
Jul 2018
Oct 2018
Jan 2019
Apr 2019
1
2
4

Implied Relative Risk Aversion

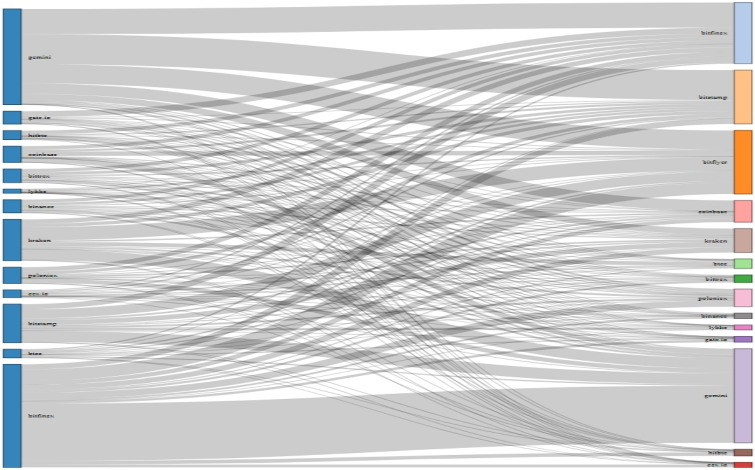


	Price Differences (in%)					
	(1)	(2)	(3)	(4)	(5)	(6)
Volatility	6.733***		6.749***	6.333***		
	(17.13)		(17.17)	(16.09)		
Latency (Median)		0.006***	0.006***	0.007***		
		(5.21)	(5.23)	(5.24)		
Latency (SD)				0.001***		
				(5.72)		
Arbitrage Boundary					0.968***	1.354***
					(26.80)	(27.74)
Boundary × Margin Trading						-0.750***
						(-10.51)
Margin Trading	1.585***	1.763***	1.587***	1.551***	1.432***	2.129***
	(23.67)	(26.84)	(23.69)	(23.00)	(21.44)	(23.43)
Spread	0.281***	0.403***	0.282***	0.280***	0.239***	0.196***
	(5.83)	(8.56)	(5.86)	(5.80)	(5.00)	(4.05)
Number of Confirmations	1.164***	1.133***	1.166***	1.189***	0.969***	0.889***
	(53.05)	(52.22)	(53.09)	(53.04)	(44.24)	(40.28)
Tether	0.617***	0.483***	0.614***	0.670***	0.357***	0.201***
	(8.21)	(6.44)	(8.17)	(8.80)	(4.85)	(2.69)
Business Account	-0.791***	-0.761***	-0.796***	-0.829***	-0.911***	-0.957***
	(-9.18)	(-8.94)	(-9.25)	(-9.59)	(-10.63)	(-11.17)
Exchange Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	.23	.22	.23	.23	.23	.23
Exchange-Hour Observations	178,215	178,215	178,215	178,215	178,215	178,215

6. Limits to Arbitrage and Cross-Exchange Flows

Flow dataset

- We identify 62 million wallets associated to 15 exchanges in our sample
- 3.7 million transactions with 54 million USD average daily volume



Exchange flows and arbitrage opportunities

- We estimate the simple linear model

$$y_{i,t} = \alpha_i + \beta x_{i,t} + \varepsilon_{i,t},$$

where $y_{i,t}$ are (hourly) flows between exchanges and $x_{i,t}$ are different measures of price differences.

	Exchange Flows (in USD)		
	(1)	(2)	(3)
Price Differences	182.263 (0.00)		
Price Differences Adjusted for Transaction Costs		84.945*** (6.65)	
Price Differences Adjusted for Transaction Costs in Excess of Arbitrage Boundaries			111.010*** (4.57)
Exchange Pair Fixed Effect	Yes	Yes	Yes
Observations	39,246,152	39,246,152	38,806,690

Conclusions

Stochastic latency imposes limits to arbitrage

Key friction of blockchain-based settlement systems

Quantitatively important friction in Bitcoin markets

- Arbitrage bounds range around 90bp
- On average, 75% of all cross-market price differences are explained by stochastic latency solely.
- Additionally accounting for trading costs, 95% are captured.

Far reaching implications:

- Reduction of price efficiency; hindering price discovery
- Pricing of securities difficult; risk-neutral probabilities not unique
- Market makers have more room for quoting